

Optical fibre communication system

This invention relates to optical fibre communication systems and, in particular to communication systems which employ solitons or soliton-like pulses for data transmission. It is also applicable to systems in which the launch pulse may be phase modulated return-to-zero (RTZ). In such systems, which are not obviously soliton-like, after travelling a distance, the pulses are transformed into soliton-like pulses.

It has recently been shown that a new class of optical solitons occur in dispersion managed systems where alternating sections of negative (anomalous) and positive (normal) dispersion fibre are used. (See, for example, Suzuki, M., Morita, I., Edagawa, N., Yamamoto, S., Taga, H., and Akiba, S., 'Reduction of Gordon-Haus timing jitter by periodic dispersion compensation in soliton transmission', *Electron. Lett.*, 1995, 31, (23), pp. 2027-2029, Smith, N.J., Knox, F.M., Doran, N.J., Blow, K.J., and Bennion, I., 'Enhanced power solitons in optical fibres with periodic dispersion management', *Electron. Lett.*, 1996, 32, (1), pp54-55 and Smith, N.J., Forysiak, W., and Doran, N.J., 'Reduced Gordon-Haus jitter due to enhanced power solitons in strongly dispersion managed systems', *Electron. Lett.*, 1996, 32, (22), pp2085-2086.

In a further paper entitled 'Energy scaling characteristics of solitons in strongly dispersion-managed fibres', *Opt. Lett.*, 1996, 21, (24), pp1981-1983, Smith et al. derived an empirical relationship for the enhanced power of these solitons, where the average dispersion is anomalous and significantly less (in magnitude) than the dispersion in the two segments. These lossless calculations showed the importance of the launch point in the map (the minimum chirp is at the centre of either section), but did not establish the exact pulse shape, nor the long term stability of the pulses.

We have discovered that by using dispersion management, in which an optical communication system uses alternative sections of fibre of opposite sign of dispersion, that transmitted pulses are not distorted (neither dispersively nor effectively nonlinearly) provided the correct form of the pulse is selected. It is possible to have stable pulses (solitons) where the net dispersion is zero, normal or anomalous. There are no solitons for normal dispersion, but pulses are also stable in this regime. This permits wavelength multiplexing around the zero dispersion since, although the dispersion depends on

wavelength, it is unavoidable that both signs will occur. However, the new arrangement permits solitons to be used for a wide range of wavelengths.

We have found that the shape of pulse is significant. For these systems it is important to pre-chirp the pulse in an appropriate way. The degree of chirp and pulse
5 duration depends on the data rate required and how the map is designed.

We have also discovered that for zero net dispersion there appears a preferred pulse duration for a particular map. The ratio $\frac{\ddot{\beta}\ell}{\tau} \sim 4$, where $\ddot{\beta}$ is the fibre dispersion, τ is the pulse duration and ℓ is the fibre length. It means that the system (for the zero dispersion case) is specified by the pulse duration (effectively the data rate) and the
10 dispersion of the fibres i.e. the length of each section can be immediately inferred. For example if $\tau = 20\text{ps}$ (10Gb/s) and $\ddot{\beta} \sim 20\text{ps}^2/\text{km}$ (standard fibre), then the fibre lengths should be 80 km. Alternatively, if $\ddot{\beta} = 1\text{ps}^2/\text{km}$ (dispersion shifted fibre typical number) then 1600 km is ideal. Numerical modelling indicates that there are stable nonlinear transmission pulses for periodically dispersion managed systems where the
15 path average dispersion may be either anomalous, zero, or even normal.

A new class of stable pulses is demonstrated to exist when the average dispersion is zero or even normal. The discovery of these stable pulses allows the use of solitons in WDM systems around the zero (average) dispersion, where due to dispersion slope effects both signs of dispersion are inevitable.

20 According to one aspect of the present invention there is provided a soliton or soliton-like pulse-based optical communication system comprising a length of optical fibre divided into a plurality of sections wherein the average dispersion of the length of fibre is significantly different from the dispersion of each section.

According to a further aspect of the present invention there is provided a soliton or
25 soliton-like pulse-based optical communication system comprising a length of optical fibre divided into a plurality of sections wherein the average dispersion of the length of fibre is significantly different from the dispersion of each section and wherein the pulse duration τ is substantially equal to $\frac{1}{4}\ddot{\beta}\ell$ where $\ddot{\beta}$ is the fibre dispersion, τ is the pulse duration and ℓ is the fibre length.

The invention will be particularly described by way of example, with reference to the accompanying drawings, in which

Figure 1 shows propagation for 100 000 km for a pulse with $E = 0.03$ pJ, and 100 km sections of $\beta'' = -5.1 \text{ ps}^2/\text{km}$ and $\beta'' = 4.9 \text{ ps}^2/\text{km}$. The pulse is shown at the mid point of the anomalous section

Figure 2 shows propagation over one cycle for a pulse with $E = 0.03 \text{ pJ}$, and 100 km sections of $\beta'' = -5.1 \text{ ps}^2/\text{km}$ and $\beta'' = 4.9 \text{ ps}^2/\text{km}$

Figure 3 shows stable propagation for 80 000 km at net zero dispersion for a pulse with $E = 0.2 \text{ pJ}$, and 80 km segments of $\beta'' = \pm 10 \text{ ps}^2/\text{km}$. The pulse is shown at the mid point of the anomalous section,

Figure 4 shows the pulse width versus energy for a dispersion map with zero average dispersion. (a) at the segment boundary, (b) in the mid point of the normal segment, (c) in the mid point of the anomalous segment;

Figures 5 to 7 are dispersion maps illustrative of the invention, and

Figure 8 is a schematic diagram showing a soliton or soliton-like communication system in accordance with a specific aspect of the invention.

We have performed extensive numerical investigations on a two stage map for individual pulses, ignoring loss in the first instance. Our procedure is first to accurately establish the long distance stable solution if it exists. In general, if one starts with some reasonable initial pulse shape and size, then the pulse width, taken at a fixed point in each cycle, will oscillate over many cycles, as some radiation is shed and the long term stable pulse emerges. We use this effect by averaging the pulse shapes at the extreme of these oscillations to rapidly find the converged wave form with high accuracy. We can then remove the averaging to check the stability of the converged pulses.

Using this technique we have discovered that long term stable pulses can indeed be obtained, provided that the average dispersion is significantly different from the dispersion in each section. Figure 1 shows an example of such a pulse for a deep map with net anomalous dispersion and a power enhancement factor of 4.5. The evolution shows no evidence of radiation and is shown on a log scale to illustrate the extreme stability observed. Figure 2 shows the evolution during one period of the map. At the mid point of each section, the pulse has a curved (Gaussian) centre and linear

(exponential) wings with dips. At these points the pulse is totally unchirped, i.e. exactly in phase, and the dips are zeroes, roughly periodic in t^2 . At the boundary between sections, where the pulse is widest, it becomes more sech-like (exponential) and is strongly chirped. These observations are typical for strong dispersion maps. Contrary
5 to normal assumptions, the pulse is not self-similar during one cycle, i.e. the power spectrum also evolves.

The most surprising result of our investigation is that such stable pulses exist not only for many different types of map with average anomalous dispersion, but also for maps with exactly balancing sections, i.e. zero average dispersion, and even where the
10 average dispersion is normal. In each case the pulse is similar to the one illustrated in Figures 1 and 2. For instance, Figure 3 shows a stable pulse for one case where there is no net dispersion. This is a remarkable result, since this pulse is certainly nonlinear, and there is no net dispersion against which to balance the nonlinearity in a conventional sense, yet the pulse does not show any spectral broadening. In this case it is clearly
15 inappropriate to discuss a power enhancement, but for the parameters of Figure 3 the pulse energy is equivalent to that of a conventional soliton with the same width for a constant dispersion of $-2.5\text{ps}^2/\text{km}$. This is clearly a significant energy and will allow stable soliton-like operation at zero dispersion. Indeed we have found that, in contrast to what is seen in systems without dispersion control, including third order dispersion of
20 $0.07\text{ps}/\text{km}$ does not lead to a break-up of the pulse.

In the case of net normal dispersion, we have the equally surprising result that dispersion management allows exact nonlinear suppression of dispersion for these bright soliton-like pulses. We have obtained stable pulses for small values of the net normal dispersion, e.g. 80km segments with a dispersion of $-10\text{ps}^2/\text{km}$ and $+10.8\text{ps}^2/\text{km}$
25 respectively. This of course is not possible with conventional bright solitons for uniform normal dispersion.

We have also investigated the dependence of the pulse width on the energy. For illustration, we consider the case of zero average dispersion, where there is effectively only one independent parameter after appropriate scaling. Figure 4 shows the energy
30 dependence of the pulse width for a particular map ($\ell_{1,2} = 80\text{ km}$ and $\beta_{1,2} = \pm 10\text{ps}^2/\text{km}$). There is a nearly linear dependence on energy of the pulse width, increasing in the

normal fibre and decreasing in the anomalous fibre, in contrast to conventional solitons, where the energy is inversely proportional to the pulse width, so that the pulse width goes to infinity as the energy goes to zero. Here we have observed that for a particular map there appears to be a 'preferred' optimal pulse width for small pulse energies.

5 We have also performed extensive studies of our new stable pulse and discovered that the energy enhancement depends on the average dispersion and the depth of the map in a complex manner.

The remarkable stability and the possibility of ultra-stable soliton-like propagation for dispersion of either sign (or zero) clearly implies that high data rate long distance
10 soliton communication should be possible around the net zero dispersion. By operating at very low average dispersion, timing jitter effects can be virtually eliminated for a range of wavelengths, thus allowing WDM without the need for sliding filters nor active control.

Stable dispersion managed soliton-like pulses exist for anomalous and zero, as
15 well as for normal, average dispersion. The region of observation is extensive in the net anomalous dispersion and therefore these pulses are suitable for long distance and WDM systems. Appropriately tailored initial pulses can be obtained from our numerical procedure, to achieve optimal performance. The correct pulse shape depends on the position in the cycle and thus on the launch point.

20 The region of allowed dispersion is considerably extended if the anomalous element is longer (or more nonlinear) than the normal fibre(element). Thus gratings for dispersion compensation will allow larger net normal dispersion for the same map strength. Thus there is a wider wavelength range for the asymmetric map with the anomalous section the longer one. (The reverse is true if the asymmetry is the other
25 way around).

Dispersion managed solitons are excellent media for high-speed optical communication. Compared to standard solitons, their power is enhanced, they can propagate at zero and normal average dispersion, leading to reduced Gordon-Haus jitter, reduced pulse interaction and increased noise margins. We have found that by using
30 asymmetric maps the soliton power can be further enhanced and the accessible bandwidth in the normal average dispersion regime can be increased. For systems using

wavelength- division- multiplexing (WDM), asymmetric maps can equalise the soliton power in adjacent channels. The critical map strength, however, is unaffected by the map asymmetry, and the optimal strength for dispersion managed soliton systems is of the order 4.

5 In a two-stage map, where the dispersion alternates between normal and anomalous the pulse evolution is modelled by the nonlinear Schrödinger (NLS) equation

$$iu_z = \frac{\beta''}{2}u_{tt} + \gamma|u|^2u$$

where z is the distance of propagation, t is the local time, β'' and γ are the dispersion and the nonlinear coefficient of the fibre, respectively. The pulse evolution in lossy fibres can also be modelled by this equation as long as the amplification period is different from the period of dispersion management. The stationary solutions in a two-stage map are characterised by three parameters, the map strength, $S = |\beta''_1 L_1 - \beta''_2 L_2|/\tau_{FWHM}$ (subscript 1 and 2 refer to the normal and the and the anomalous dispersion fibre, respectively, L_n are the fibre lengths and τ_{FWHM} is the full width at half maximum at the mid-point of the anomalous fibre), the normalised average dispersion, $\beta'' = \beta''_{ave}/\beta''_2$ (β'' is the average dispersion) and the map asymmetry $\delta = (\gamma_1/\beta''_1)/(\gamma_2/\beta''_2)$. The map strength is the normalised length of the dispersion map, β'' is the average dispersion in fractions of the local dispersion of the anomalous fibre, the map asymmetry indicates how equal the fibres are with respect to nonlinear effects. For two fibres with equal nonlinear coefficients ($\gamma_1 = \gamma_2$), δ is the ratio of the dispersions and around zero average dispersion this is just the ratio of the lengths, $\delta = L_1/L_2$.

By using the variational approach of A. Berntson, N.J. Doran, W. Forysiak and J.H.B. Nijhof, *Opt. Lett.* and D. Anderson, *Phys. Rev. A* 27, 3135 (1983), we can calculate approximately the normalised power, $N^2 = \gamma_2 P_0 \tau_{FWHM}^2 / |\beta''_2|$ of the dispersion managed soliton as function of map strength S , normalised average dispersion and map asymmetry δ , without further assumptions. The physical significance of N^2 is that it represents the power in fractions of the fundamental soliton power at the mid-point of

the anomalous dispersion fibre. The result of this calculation is shown in Figure 5 for three cases with different asymmetry. Figure 5a ($\delta = 10$) shows the case of dispersion-shifted fibre (DSF) compensated by standard fibre (SSMF), Fig 5b ($\delta = 1$) illustrates the symmetric case (equal magnitude of the dispersion), and Fig 5c ($\delta = 0.1$) shows the case of SSMF upgraded by dispersion compensation fibre (DCF). The figures are contour plots, each line corresponding to fixed normalised average dispersion in the map strength/power plane. The variational predictions of Fig. 5 were qualitatively verified by numerical simulations presented in Fig 6.

The basic structure of the maps of Figures 5a-c is the same. In each, there is a critical strength, $S_c = 4.8$ (numerically $S_c = 3.9$, see Fig 6b), for propagation at zero and normal average dispersion. The critical strength is independent of the map asymmetry. The lower energy branch in the normal dispersion region is unstable and cannot be found numerically, see Fig 6a. The changes in Fig. 5 as the map asymmetry is decreased, is that the dispersion is shifted towards more anomalous (or less normal) on the average, i.e. the region for normal average dispersion grows when going from Fig. 5a to Fig. c. This can be explained by noting that in the normal dispersion fibre nonlinear and dispersive effects cause a frequency chirp of the same sign. Nonlinear chirping can then replace dispersive chirping and the normal fibre can be shortened as it becomes more nonlinear.

Comparing the soliton parameters for the cases shown in Fig. 5, the highest power, for a given average dispersion, is achieved for SSMF compensated by DCF (Fig. 5c). This case also gives the largest bandwidth in the normal average dispersion region, see Fig. 7. Fig. 7 shows the same data as in Fig 5 but presented differently. The lines for constant map strength penetrate deeper into the normal dispersion regime for low δ) and this corresponds, via the dispersion slope, to a larger bandwidth. This means that the chances for experimental observation of dispersion-managed solitons in normal average dispersion will be better for low δ (SSMF+DCF). The accessible bandwidth is in this case approximately ten times larger than in Fig 7a (DSF+SSMF). Finally, Fig. 7 shows that the variation of the soliton power with average dispersion is lowest for low δ . For systems using WDM, this gives an equalisation of the power in adjacent channels.

The region marked "higher order solutions" in Fig. 5 corresponds to a situation where the length of the anomalous dispersion fibre is longer than a soliton period. This region is excluded in Fig. 5 partly for the sake of clarity but also because in the variational approximation the same solution can always be achieved by a shorter anomalous fibre, i.e. with lower average dispersion.

Thus asymmetric dispersion maps can be used to optimise the performance of dispersion managed soliton systems. In particular, a system with SSMF compensated by DCF has higher soliton power, gives more bandwidth in normal average dispersion, and results in an equalisation of the channel power in WDM systems compared to symmetric systems and systems using dispersion-shifted fibres.

A soliton-based communications system is shown in Figure 8. This comprises a source of solitons T and an optical waveguide consisting of successive elements $A_1, B_1 - A_n, B_n$ having successively normal and anomalous dispersion. The elements B_1 etc. provide compensation for the dispersion in the elements A_1 . The normal dispersive elements may be provided with a bandpass filter (Fig. 8b), ideally in the centre of the element where the bandwidth is minimum. Such filters will permit relaxation of the parameter S so that $S = 2$ is suitable with appropriate filters inserted. Dispersion compensation may be performed either with fibres having anomalous dispersion or with linear elements such as Bragg gratings G (Fig. 8c). In such an arrangement it will be necessary to provide a circulator C.

Dispersion management as herein described permits operation exactly at zero dispersion for a very high speed single channel or wavelength division multiplexing around the zero dispersion point. If WDM around zero dispersion is employed, care is needed to avoid channels with identical group velocities. If this cannot be avoided it will be necessary to include a 'double' step around the centre of the system.

Dispersion slope compensation may take place, either in the compensating element or periodically or at the end of the system. Sinusoidal variations in dispersion are also suitable for all the situations described above.